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Octane Response in a Downsized, Highly Boosted Direct Injection Spark Ignition Engine

S.M. Remmert, R.F. Cracknell, R. Head, and A. Schuetze
Shell Global Solutions

A.G.J. Lewis and S. Akehurst
Univ. of Bath

J.W.G. Turner and A. Popplewell
Jaguar Land Rover

ABSTRACT

Increasingly strict government emissions regulations in combination with consumer demand for high performance vehicles is driving gasoline engine development towards highly downsized, boosted direct injection technologies. In these engines, fuel consumption is improved by reducing pumping, friction and heat losses, yet performance is maintained by operating at higher brake mean effective pressure. However, the in-cylinder conditions of these engines continue to diverge from traditional naturally aspirated technologies, and especially from the Cooperative Fuels Research engine used to define the octane rating scales. Engine concepts are thus key platforms with which to screen the influence of fundamental fuel properties on future engine performance.

'ULTRABOOST', a collaborative research project which is co-funded by the Technology Strategy Board (TSB), the UK's innovation agency, is a downsized, highly boosted, 2.0L in-line 4 cylinder prototype engine, designed to achieve 35% CO_2 emissions reduction without compromising the performance of a 5.0L V8 naturally aspirated production engine. To probe engine response to fuel, a matrix of 14 formulations was tested at several engine conditions. This is the first in a series of fuel related papers and focuses on the engine's response to the research octane number (RON). The knock limited spark advance was determined for a series of fuels with RON varying from 95 to 112; octane was shown to provide 5 or 10° crank angle advance in knock limited spark advance at 2000 and 3000 rpm, respectively. This study demonstrates that fuel octane quality continues to be important for the performance of emerging downsized engine technologies. Furthermore, the trend for continued engine downsizing will increase the potential performance benefit associated with knock resistant fuels.

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INTRODUCTION

Gasoline spark ignition (SI) engine development is driven in part by increasingly ambitious global targets for fleet-average CO_2 emissions. For example, European emissions legislation requires fleet average CO_2 emissions to meet 130g/km by 2015 and 95 g/km by 2020 [1]; while US policies will require CO_2 emissions targets of 101 g/km (163 g/mile) by 2025 [2]. Conversely, maintaining a vehicle's power and performance credentials is important to customers, especially in the premium vehicle market [3]. Therefore, a key area of engine research and development relies on improving combustion efficiency and reducing losses, such that an engine's fuel consumption targets can be met without compromising performance.

Engine Downsizing and Ultraboost

While a variety of strategies exist for engine development to achieve improved efficiency [4], engine downsizing is a major industry trend that - in combination with pressure charging of the intake air - enables improved efficiency by running the engine at a higher specific output for the same torque at a given engine speed, yet reducing pumping and frictional losses [5, 6]. Similar or improved engine performance is often maintained across the engine map through intake air charging strategies (super- and turbocharging), variable valve events, and cooled external exhaust gas recirculation (EGR) [4, 6].

'ULTRABOOST' is a collaborative research program, co-funded by the Technology Strategy Board (TSB), the UK's innovation agency, involving the following technical consortium partners: Jaguar Land Rover (JLR), Shell Global Solutions, Lotus Engineering, GE Precision Engineering, CD-Adapco, University of Bath, Imperial College London, and the University of Leeds, as outlined in Table A.1.

The aim of the Ultraboost project was to develop an engine concept that - relative to a baseline 5.0L, naturally aspirated (NA) V8 Euro 5 production engine (the Jaguar Land Rover AJ133[7]) - would be able to reduce tailpipe CO_2 emissions by 35% over the New European Drive Cycle (NEDC) in a Sports Utility Vehicle, without compromising performance. This ambitious CO_2 reduction target places the Ultraboost engine in the Euro 6-7 emissions class [8].

Fuel Octane & Engine Performance

Fuel chemistry, and particular fuel octane quality, can play a large role in the performance of SI engines, which can be achieved in part via optimal combustion phasing; namely, a sufficiently advanced spark timing (Minimum (advance) for Best Torque, MBT). Advancing the spark timing to MBT can be restricted by an abnormal combustion process known as knock - auto-ignition of the end gas ahead of the flame front - which limits performance and can cause engine damage in extreme cases [9]. Knock resistance of a fuel formulation is traditionally characterized by the Research Octane Number (RON) and Motor Octane Number (MON) scales as determined in a Cooperative Fuels Research (CFR) engine [10]. The RON and MON ratings for a fuel are defined by the volume percent of iso-octane mixed with *n*-heptane required to achieve the same knocking behavior.

Recent engine developments are increasing the gap between modern direct injection (DI), boosted technology and that of the CFR engine [11, 12]; especially in terms of the in-cylinder temperature and pressure history experienced by the end-gas ahead of the flame front, which drives engine knock response [4, 9, 11, 13, 14, 15, 16]. The Ultraboost concept engine is at the leading edge of downsized, boosted engine technologies, and is therefore a key platform from which to understand the impact of fuel octane quality on performance.

A series of experiments were performed with the Ultraboost engine on a Combustion Air Handling Unit (CAHU), for full control of experimental conditions, to probe the engine's response to various fuel properties. This paper is the first in a series of publications on fuel experiments with the Ultraboost engine. The focus of this study was to ascertain the influence of RON on engine performance, in order to evaluate the impact of octane in emerging, downsized engine technologies[1].

EXPERIMENTAL DESIGN

Engine Configuration

The Ultraboost engine design and control systems are described in detail in references [3, 6, 8, 17, 18], and therefore only briefly summarized here. The Ultraboost concept engine is a 2.0L (60%) downsized in-line, 4 cylinder engine constructed from one bank of the base AJ133 engine. The engine has a new cylinder head and combustion system, with variable valve timing, cam profile switching, both direct injection and port fuel injection (PFI) capabilities, and high flow and tumble inlet ports. Low pressure, cooled external EGR and a water cooled exhaust manifold (WCEM) are also key design features enabling the engine to be run under stoichiometric conditions for improved fuel economy.

Table 1. Ultraboost Engine Details [6]

Engine Details	
Engine Type	4 cylinder in-line, 4 valves per cylinder
Capacity (cc)	1991
Bore (mm)	83
Stroke (mm)	92
Compression Ratio	9.0:1
Firing Order	1-3-4-2
Construction	All-aluminum AJ133 cylinder block (right bank)
Combustion System	Pent-roof combustion chamber Asymmetrical central DI and spark plug High-tumble intake ports Auxillary port-fuel injection (not used in these experiments)
Valve Train	Chain-driven double overhead camshafts, fast acting dual continuously variable camshaft phasers (DCVCP) Cam profile switching (CPS) tappets on inlet and exhaust
Specific Power	142 (kW/l) @ 6500 rpm
Specific Torque	255 (Nm/l) @ 3500 rpm
Maximum BMEP	~35 bar @ 3500 rpm and ~25 bar @ 1000, 6500 rpm
Other	External cooled EGR, Water cooled exhaust manifold 130-145 bar peak pressure limit
Engine Test Facilities	
Dynamometer	Twin dynamometer arrangement (AVL 215kW AC dynamometer and Froude AG250 Eddy current dynamometer)
Emissions Bench	MEXA 7000 Series with EGR
Cylinder Pressure Sensors	Kistler type 6054 (air cooled)
Cylinder Pressure Acquisition	AVL Indiset

Various boosting strategies have been investigated; to achieve performance across all engine speeds, a two-stage series super and turbocharger configuration with an inter- and after-cooler was chosen [8]. The CAHU at the University of

1. Fuels of varying RON and approximately fixed sensitivity (S=RON-MON) are the subject of this investigation. A future communication will explore the effects of decoupling RON and MON.

Bath was used to simulate the integrated super- and turbo-charger system, for early-stage optimization of the combustion system and for the duration of the fuels experiments. Furthermore, throughout the fuels experiment, the engine was run in direct injection mode only (no PFI). Details of the engine and test cell are shown in Table 1 and Figure 1.

To meet the performance target of the base AJ133 engine, the Ultraboost engine was required to be charged up to 3.5 bar absolute and meet challenging brake mean effective pressure (BMEP) targets. The performance target of the Ultraboost engine in comparison to other engine concepts is shown in Figure 2. Ultraboost engine development progress is presented elsewhere [3, 6, 8, 17, 18]; tests have shown that the Ultraboost target torque curve is achievable with the selected boosting system above 1500rpm due to the steep turbocharger run-up line [6, 19].

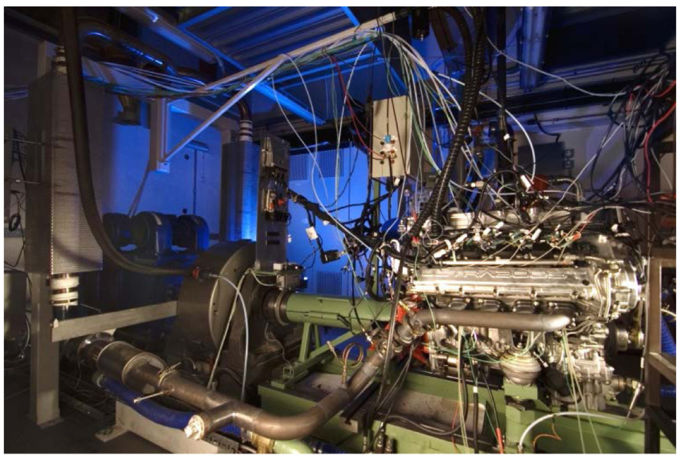


Figure 1. Ultraboost Engine Installed at University of Bath Test Facilities.

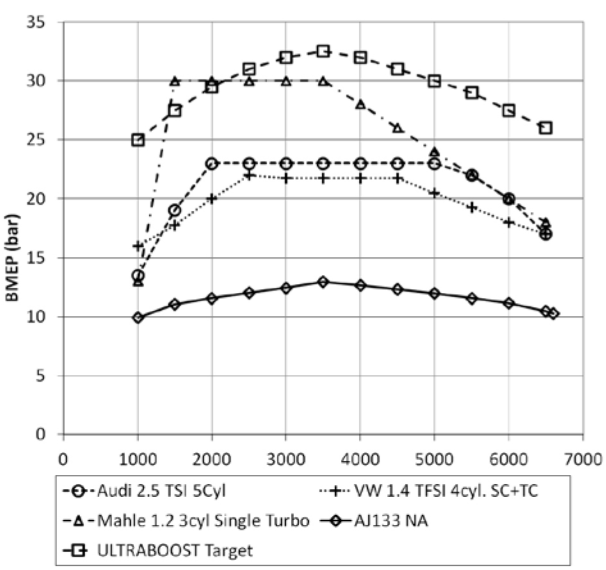


Figure 2. BMEP Performance Target of the Ultraboost Concept Engine in Comparison to Production and Concept Engines

Fuel Properties

A matrix of 14 fuels was tested in the Ultraboost engine, in order to probe the response of a highly boosted, downsized engine to a variety of fuel properties including octane, sensitivity, flame speed, and oxygenate content. The focus of this paper is on a subset of five of these fuels, chosen to probe the engine's response to octane (RON) as a means of understanding the potential performance benefit provided by premium octane fuels in emerging engine technologies. The results of the remaining fuels experiments will be the subject of future communications.

The details of the five fuels chosen for this experiment are shown in Table 2. The "Base" fuel was used throughout the engine development process and is included as a reference case. The fuels vary in RON from the minimum EN228 compliant fuel (H) with a value of 95.1, to a very high octane fuel dosed with a synthetic octane boosting component (G), with a RON value of 111.6. Only fuels of similar levels of sensitivity are presented; from 10.1 to 12.6; the influence of fuel sensitivity on performance in Ultraboost is the subject of a future communication and is not discussed here.

The fuels vary in terms of oxygenate content; the Base fuel used in engine development contained 5% ethanol by volume, as did fuel H. Fuels I and G contained 0% ethanol, and Fuel B contained 10.5% methyl tert-butyl ether (MTBE). This variation in oxygenate content could contribute to differences in engine performance via charge cooling or flame speed; however, the auto-ignition properties of the fuel formulation are considered to be the dominant factor under high load, knocking conditions. Furthermore, the distillation properties of the fuel blends are relatively well matched, as shown in Figure 3, with the exception of fuel G, which has an atypically low level of material boiling below 100°C (10%v cf. 60%v). Again, octane is considered to be the primary fuel property in this experiment, though distillation properties can affect spray formation and hence adequate mixing and efficient combustion [20].

Table 2. Details of Test Fuel Formulations

	H	Base	I	B	G
RON	95.1	97	98.7	101.4	111.6
MON	85	85.3	86.5	88.8	101.2
S	10.1	11.7	12.2	12.6	10.4
LHV (MJ/kg, gas)	43.0	43.1	43.3	42.2	42.4
Density (g/cm^3)	0.748	0.743	0.735	0.754	0.795
Oxygenate Content	E5	E5	E0	10.5% MTBE	E0

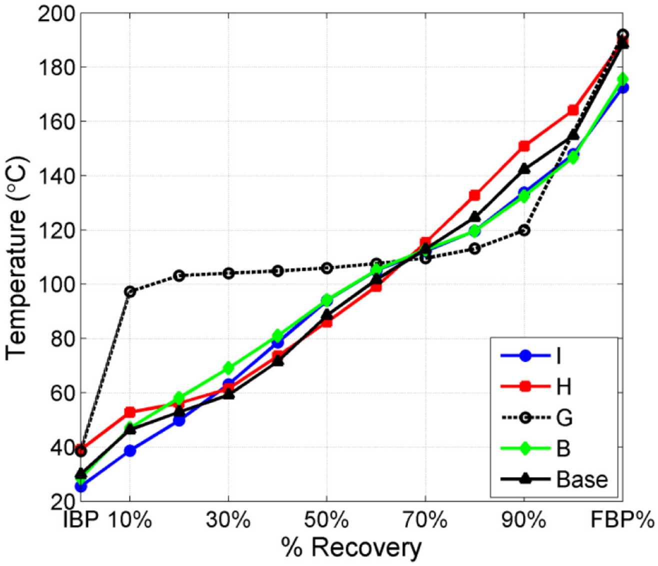


Figure 3. Distillation Properties of Test Fuels. Fuels have similarly matched properties with the exception of Fuel G.

Test Design

The full matrix of 14 fuel formulations was tested over a fixed cycle order of 8 engine test conditions, chosen to reflect different areas of engine operation. Each fuel was tested once, with the exception of the Base fuel, which was tested five times over the course of the experiment to evaluate repeatability. At four instances during the engine experiment (before the first four Base fuel repeats), lubricant was flushed to fresh semi-synthetic 5W-20 oil, followed by a 9 hour de-greening procedure with four repeats of the complete engine test cycle.

Approximately two experiments were performed per day; fuel test order was determined according to alternating high and low RON to aid in adequate determination of fuel flushing via engine stabilization of the knock limit. Approximately 1.5L of fuel was required to flush the engine system when running at the daily stabilization condition of 2000 rpm, mid-load.

Engine Test Cycle

The engine test cycle consisted of four target torque-speed conditions of the engine map as shown in Figure 4; a subset of these test conditions is given in detail in Table 3. These conditions were designed to investigate the fuel response properties of (1) the supercharged region of engine operation at low speed, high load, (2) the transition between non-boosted and boosted at low speed, mid load, (3) the transition between the super and turbocharged region of engine operation and mid-speed, high load[2], and (4) the turbocharged region of engine operation at high speed, high load.

2. Due to material limitations of in-cylinder pressure limits at advanced spark timings at the 3000 rpm high load condition, engine operation was adjusted as follows to allow for knock rather than pressure limited experiments: the air charge temperature was increased from 40°C to 60°C to increase the propensity to knock. The inlet cam phasing was also reduced to retard from 60° to 45° reducing the valve overlap and air flow so that KLSA was reached before maximum pressure limit. The BMEP achieved at 3000rpm for fuel matrix testing ranged from 19 to 27 bar across the spark sweep, whereas peak value for full load engine operation is 32 bar.

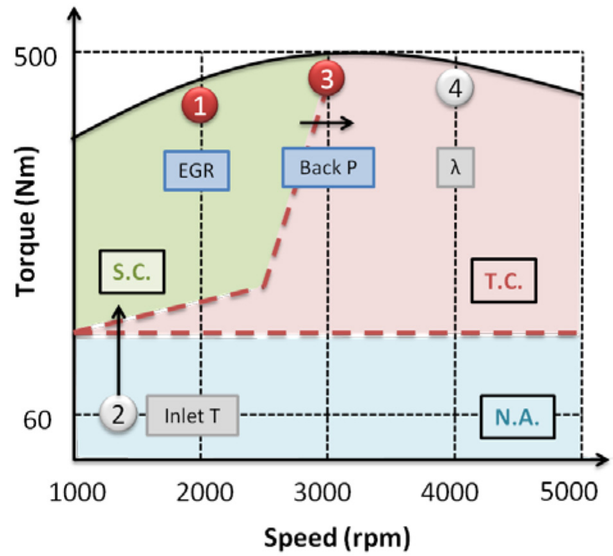


Figure 4. Schematic of Engine Test Cycle. (1) Supercharged bias with variable EGR; (2) Non-boosted with variable inlet air temperature, (3) Transition between super- and turbocharged bias with variable back pressure, and (4) Turbocharged bias with variable λ. (1) and (3) are the focus of the current study.

One parameter was varied at each of the four torque-speed conditions; at condition (1) the effect of percent external EGR was evaluated via test 1A (low) and 1B (high); at condition (2) the influence of boost temperature was investigated via 2A (low) and 2B (high); and at test condition (3) the influence of back pressure was evaluated via test 3A (low) and 3B (high). Finally, at test condition (4) the effect of lambda was evaluated via 4A (stoichiometric) and 4B (rich). Although the details of the full engine test cycle are discussed here for completeness, only the knock limited high load test conditions (1) and (3) are the subject of the current report.

The engine test cycle details for conditions (1) and (3) are given in Table 3. The torque target was set slightly lower than the maximum torque curve to avoid in-cylinder pressure limitations. At each of the four conditions, the boost pressure was set such that the target torque was met with the Base fuel; the boost pressure was subsequently held constant for all remaining fuel formulations tested at that engine condition. For 1B (10% EGR), the boost pressure was increased such that the Base fuel was able to achieve the same target torque as for 1A (0% EGR); this set the boost pressure conditions for all remaining fuels.

Each fuel was run through the test cycle in a fixed order: stabilization condition, 1A, 1B, 2A, 2B, 3A, 3B, 4A and 4B. At test conditions (1) and (3), the spark timing (ST) was advanced until the knock limited spark advance (KLSA) was reached, as determined by the average knock peak (KP) of the 4-cylinders, via the standard AVL algorithm[3]. At each of the ten recorded ST conditions, the engine was stabilized for 30 seconds before

3. Knock peak is defined as the maximum knock amplitude of the band-pass filtered in-cylinder pressure trace.

recording in-cylinder data (ST, KP, mean effective pressure, combustion phasing, etc), averaged over 10 seconds of data recording.

Table 3. Details of Engine Test Cycle

Condition	1A	1B	3A	3B
Speed	2000		3000	
BMEP (bar) [ST Dependent]	25-31		21-26	
Boost Pressure (bar)	2.3	2.5	2.4	
Back Pressure (bar)	1.45		1.7	2.2
EGR %	0	10	10	
Boost Temperature (˚C)	40		60	
λ	1.0		1.0	
Within test variable	ST to KLSA		ST to KLSA	
Data points	10		10	

RESULTS AND DISCUSSION

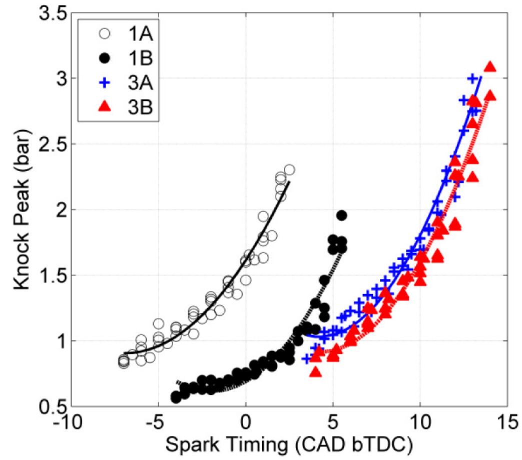
Engine Condition Stability

The values for boost temperature, boost pressure, back pressure and EGR were averaged over all ST data points within a given fuel and experiment to assess test condition stability over the course of the experiment. The engine conditions were relatively stable and in alignment with the engine conditions specified in Table 3, with the exception of engine blow-by, which was shown to increase over the course of the fuels testing, potentially due to engine aging.

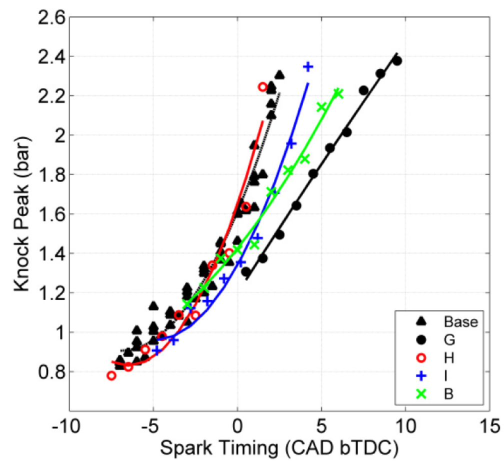
Knock Limited Spark Advance

The cylinder averaged AVL knock peak was used to systematically calculate the KLSA[4]. A quadratic equation was fit to the average KP as a function of ST; the function was interpolated or extrapolated to determine the KLSA, defined as the ST at which the KP is equivalent to 1 bar per 1000 rpm (i.e. 2 bar at 2000 rpm for condition (1) and 3 bar at 3000 rpm for condition (3)).

As 5 repeats were performed for the Base fuel, the KLSA was determined by fitting a quadratic function to the pooled data from multiple experiments as it was found that this result was very repeatable across all tests. The results for the Base fuel at all four engine test conditions are shown in Figure 5a. In general, the 2000 rpm condition is more knock limited than at 3000 rpm, resulting in less advanced values for KLSA at this engine condition. Furthermore, at 2000 rpm, comparing the results at (iso-torque) 0% EGR (1A) to 10% EGR (1B) shows that cooled external EGR has a strong role in mitigating knock and allowing for more advanced spark timings[5]. Interestingly, at 3000 rpm, the effect of higher back pressure also decreases KP for a given ST and hence allows for a more advanced KLSA. It should be noted that at 3000 rpm, both experiments were run at 10% EGR.



(a). Base Fuel at Region 1 (black): 1A (circles, open), 1B (circles, closed); Region 3A (blue +); Region 3B (red triangles, closed).



(b). Region 1A: 0% EGR, 2000 rpm, High load. Base (Black, solid triangles), G (black, closed circles), H (red, open circles), I (blue, +) and B (green, crosses).

Figure 5. Knock Peak versus Spark Timing for Knock Limited Spark Advance Determination. Lines represent quadratic fits to data. KLSA was determined when KP=2 bar at 2000 rpm and 3bar at 3000 rpm.

The KLSA versus ST plots for each fuel and experimental condition are shown for Region 1A in Figure 5b; the remaining test conditions are shown in Figure A.1. The KLSA results for all test conditions are presented in Table 4 and the relationship between RON and KLSA is summarized in Figure 6. The KLSA is strongly dependent on the fuel RON; high octane quality allows for the KLSA to advance by up to 5° CAD bTDC for the highest RON fuel (G) relative to the minimum RON fuel (H) for Region 1A. At Region 1B, the extrapolated maximum KLSA benefit was found to be 14.2°, while at Region 3A and 3B, the maximum KLSA advance was found to be 9.1° and 11.4°, respectively.

4. This paper presents cylinder-averaged results only, in order to evaluate the impact of fuel octane quality on overall engine performance. Slight cylinder-to-cylinder variations were observed, with Cylinder 2 reaching both higher in-cylinder pressures and KLSA first [18].

5. Generally this can be seen in Figure A.1. However, for quantitative comparisons it should be noted that, due to features of the test cell, Cylinder 2 was more knock limited than other cylinders, causing some of the fuels experiments not to reach an average KP of 2. As a result, the KLSA in Region 1B is extrapolated and therefore a less accurate result than that for Region 1A.

Table 4. KLSA Results and Comparison

Fuel	RON	1A	1B	3A	3B
Base	95.1	1.3	5.8	12.8	12.7
H	97.0	1.7	6.6	13.5	14.3
I	98.7	3.2	7.7	14.5	14.9
B	101.4	4.5	11.5	18.4	18.6
G	111.6	6.1	20.0	21.9	24.1
I-H	3.6	2.0	1.9	1.7	2.1
G-H	16.5	4.9	14.2	9.1	11.4

Furthermore, it can be seen in Figure 6 that the response to octane changes with region of the engine map. At Region 1, it is clear that EGR contributes to an advanced spark timing; that this effect is larger than a fuel octane effect, and furthermore, that high octane fuels provide a greater KLSA advantage at 10% compared to 0% EGR. At 3000 rpm, there is comparatively little effect due to high back pressure - smaller than effects due to fuel octane - but, similar to Region 1, high octane fuels provide a greater KLSA advantage when in-cylinder residuals are increased by a higher back pressure[6].

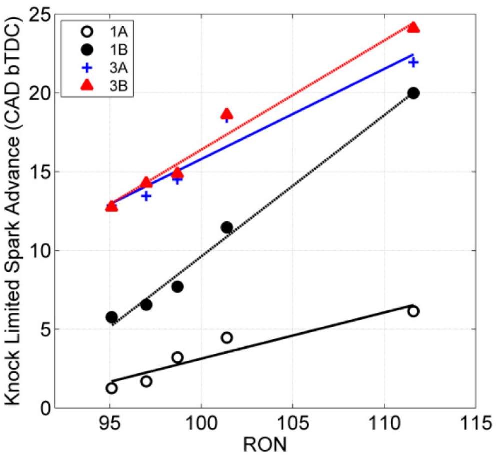
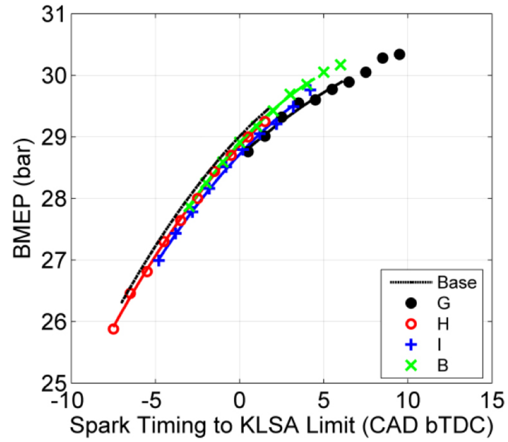


Figure 6. Knock Limited Spark Advance as a function of fuel RON with linear trend lines.1A (black, open circles), 1B (black, closed circles), 3A (blue, +), 3B (red, closed triangles).

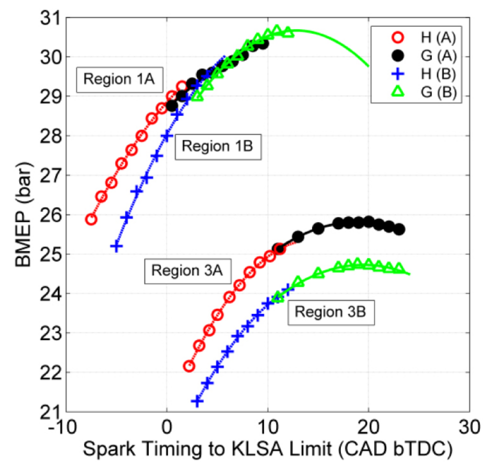
Octane Performance

The brake mean effective pressure (BMEP) and brake specific fuel consumption (BSFC) were determined for each fuel at each engine condition and ST. A quadratic fit to the data extrapolated or interpolated to the KLSA limit (Table 4) enabled comparisons of the potential performance benefits associated with fuel octane quality in the Ultraboost engine.

The detailed BMEP results for Region 1a are shown in Figure 7a and for all other engine conditions in Figure A.2. Generally, octane and hence advanced ST is the predominant factor in achieving high BMEP values; and hence performance is correlated to fuel octane quality. There are some small differences between the fuels associated with BMEP at fixed ST, which could be due to other fuel properties such as different laminar burning velocities; however, the dominant effect on performance appears to be advanced spark timing achievable via enhanced fuel octane quality[7].



(a). Region 1A: 0% EGR, 2000 rpm, High load. Base (black, dashed), H (red, open circles), I (blue, +), B (green, crosses), G (black, closed circles).



(b). Region 1 (upper left); Region 3 (lower right); Fuel H, 1A/1B (Red, dashed/open circles), Fuel G, 1A/1B (Black, solid/closed circles); Fuel H, 3A/3B (Blue, dashed/+), Fuel G, 3A/3B (Green, solid/open triangles).

Figure 7. Brake Mean Effective Pressure as a function of Spark Timing. Quadratic fit lines extrapolated to KLSA.

The BMEP results for all four engine test conditions are shown together in Figure 7b and the values at either KLSA or MBT timing are given in Table 5. Region 1 is close to and at some spark timings exceeding the BMEP target of 30 bar at the knock limit (Figure 2). By contrast, the engine condition chosen for Region 3 is limited to a BMEP value of approximately 26 bar BMEP, approximately 6 bar BMEP below the full load performance target[8]. At advanced ST, the 0 and 10% EGR

6. It is assumed that higher back pressure increases internal residuals, though for this engine and condition, this has not been verified by simulation.

7. Note that one exception to this statement is the difference in performance between fuels B and G; despite advanced KLSA of G these fuels exhibit similar BMEP at the knock limit. Thus there are additional effects such as distillation properties (Figure 3), sensitivity (S=RON-MON) and laminar burning velocity which could be important here. The latter effects will be the topic of future communications.

8. Note that this is not a performance limitation of the engine, but rather a more conservative test condition was chosen to prevent the highest octane fuel from

cases (1A and 1B) achieve similar performance, due to the higher boost pressure condition chosen for the 10% EGR case. The BMEP for the turbocharged bias, high back pressure case (3B) in comparison to the supercharged bias, low back pressure case (3A), is consistently lower across all spark timings. At Region 1A the highest octane fuel G (111.6 RON) approaches MBT timing. The BMEP result at Region 1B requires significant extrapolation to reach the KLSA and indicates that the highest octane fuel might exceed MBT timing at this condition. At Region 3A and B, this fuel enables spark advance well beyond MBT timing.

The BSFC results are shown for Region 1A in Figure 8 and for all other engine conditions in Figure A.3; the values at either KLSA or MBT timing are given in Table 5. In general, the more advanced the spark timing, the more efficient the combustion and hence the lower the fuel consumption - until MBT timing is reached. There are some differences within fuels associated with composition; Fuel I is an E0 fuel and hence has lower fuel consumption levels than the oxygenated fuels Base, H and B. Fuel G, the highest octane fuel, has surprisingly high BSFC values. This is associated with higher relative total hydrocarbon emissions values in comparison to the other fuels (data not shown); likely as a result of inadequate mixing due to the low volatility of this formulation (Figure 3).

Table 5. KLSA or MBT ST (CAD bTDC), Brake Mean Effective Pressure (bar), and Brake Specific Fuel Consumption (g/kW-h) at KLSA or MBT. Fuel G*: KLSA results at Region 1A; MBT results at all other engine conditions. All other fuels: KLSA results only.

	Result	H	Base	I	B	G*
	RON	95.1	97.0	98.7	101.4	111.6
1A	KLSA	1.3	1.7	3.2	4.5	6.1
	BMEP	29.2	29.4	29.5	29.9	29.9
	BSFC	265.7	268.0	256.6	262.4	265.6
1B	KLSA	5.8	6.6	7.7	11.5	12.7
	BMEP	30.0	30.3	30.3	30.7	30.7
	BSFC	255.6	252.6	245.8	249.5	247.2
3A	KLSA	12.8	13.5	14.5	18.4	18.8
	BMEP	25.3	25.6	25.7	26.1	25.8
	BSFC	237.4	235.4	228.8	232.7	234.1
3B	KLSA	12.7	14.3	14.9	18.6	19.6
	BMEP	24.2	24.4	24.5	24.8	24.7
	BSFC	238.1	235.1	229.5	233.0	233.9

Table 6 shows a comparison between (1) the minimum EN228 compliant RON fuel, H, (2) an intermediate level RON fuel, I, and (3) a very high octane fuel, G. Across all four engine conditions, the intermediate level fuel provides approximately 2° crank angle advance in KLSA, with an associated 1% benefit in BMEP. The high octane fuel provides approximately 5-7° crank angle advance in ST to reach KLSA or MBT, with approximately 2% benefit in BMEP.

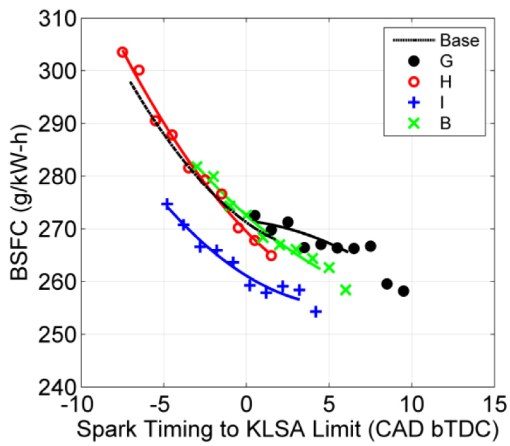


Figure 8. Brake Specific Fuel Consumption in Region 1A as a function of Spark Timing. Quadratic fit lines extrapolated to KLSA; Base (black, dashed), H (red, open circles), I (blue, +), B (green, crosses), G (black, closed circles).

Table 6. KLSA or MBT ST (CAD bTDC), Brake Mean Effective Pressure Change (%) at KLSA or MBT. * Fuel G: KLSA results at Region 1A; MBT results at all other engine conditions. All other fuels: KLSA results only.

Intermediate Comparison Fuel I-H (Δ 3.6 RON)				
	1A	1B	3A	3B
KLSA	2.0	1.9	1.7	2.1
BMEP	1.10%	0.90%	1.40%	1.20%
Comparison Fuel G-H (Δ 16.5 RON)				
	1A	1B	3A	3B
KLSA or MBT	4.9	6.9	6.0	6.8
BMEP	2.40%	2.10%	2.00%	2.20%

As shown in Table 6, higher octane fuels allow for significantly improved spark advance in the Ultraboost engine. However, it is clear that because the engine is not particularly knock limited, it is already operating in the plateau region of the BMEP versus ST curve. This suggests that further downsizing with this engine is possible, where ST differences due to fuel octane quality are expected to translate into much larger BMEP benefits.

SUMMARY & CONCLUSIONS

A series of five fuel formulations of RON varying from 95.1 to 111.6 was used to discern the response of the Ultraboost engine to increasing octane. The engine's response to octane was evaluated at four different engine conditions to discern the impact of external EGR and back pressure on octane response.

exceeding the in-cylinder pressure limit of the engine.

A large increase in RON (up to 16.5) provided an advance in KLSA by 4.9° CAD at 2000 rpm, 0% EGR, and up to approximately 11° CAD at 3000 rpm, high back pressure. Interestingly, both external EGR and higher back pressure resulted in a decreased knocking intensity at a given ST, and hence a more advanced KLSA.

Corresponding performance benefits as a result of increased KLSA were evaluated. An intermediate level octane fuel relative to the minimum RON fuel provided approximately 2° CAD advance and approximately 1% benefit in BMEP, across all engine conditions. The highest, 111.6 RON, fuel afforded spark advance up to and beyond MBT, with an approximate 2% benefit in BMEP at MBT relative to the KLSA of the minimum RON fuel. Similarly, BSFC was shown to improve (decrease) with ST and reach an optimum at MBT, though incomplete combustion of the low volatility, high octane fuel caused a relatively higher fuel consumption result.

This study has shown that octane remains an important factor in driving both power and efficiency in emerging engine technologies. Use of higher octane fuels allows for a significant improvement in spark advance in the Ultraboost engine. However, the current engine is not particularly knock limited and hence is operating in the plateau region of the BMEP versus spark advance curve, even allowing for spark advance beyond MBT timing at some engine conditions. This suggests that further downsizing or higher compression ratios are possible, in which case differences in knock limited spark advance due to octane quality are expected to translate into much larger differences in BMEP. Furthermore, it is expected that as emerging engine technologies continue to move towards downsized, highly boosted technologies such as Ultraboost, high octane fuels will continue to provide a performance benefit via enhanced knock resistance.

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CONTACT INFORMATION

Sarah.Remmert@Shell.com

Roger.Cracknell@Shell.com

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DEFINITIONS/ABBREVIATIONS

BMEP - Brake mean effective pressure

BSFC - Brake specific fuel consumption

CAHU - Combustion Air Handling Unit

CFR - Cooperative Fuels Research

CPS - Cam profile switcher

DCVCP - Dual continuously variable camshaft phasers

DI - Direct injection

EGR - Exhaust gas recirculation

JLR - Jaguar Land Rover

KLSA - Knock limited spark advance

KP - Knock peak

MBT - Minimum (advance) for Best Torque

MON - Motor Octane Number

MTBE - Methyl tert-butyl ether

NA - Naturally aspirated

NEDC - New European Drive Cycle

PFI - Port fuel injection

RON - Research octane number

SI - Spark ignition

ST - Spark timing

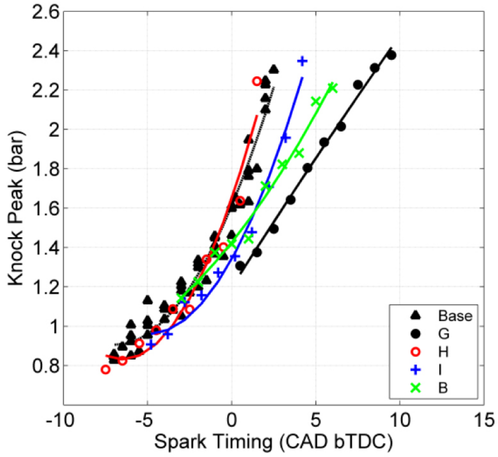
TSB - Technology Strategy Board

WCEM - water cooled exhaust manifold

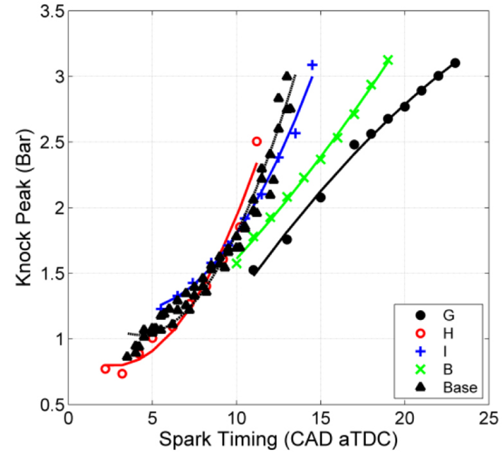
APPENDIX

Table A.1. Industry and University Partners of UK Technology Strategy Board ULTRABOOST Project

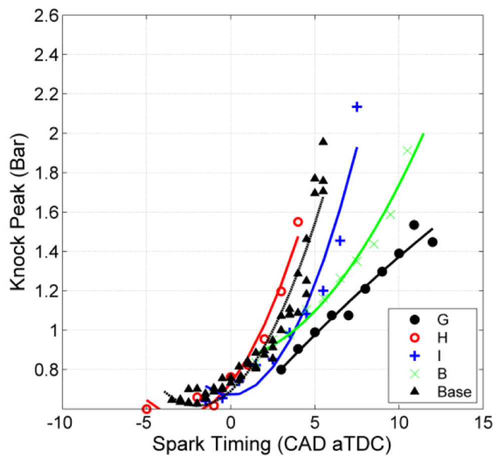
Partner	Role in Collaboration
Jaguar Land Rover	(JLR) was the lead partner, with responsibility for engine build, general procurement, engine mounted charging system integration and overall project management.
GE Precision Engineering	Provided engine design and machining capabilities as well as background knowledge on the design of high-specific-output racing engines.
Lotus	Provided dedicated engine management systems (EMS), 1-D modeling and know-how on pressure charged engines, and support for engine testing.
CD Adapco	Supported the design process with steady-state and transient CFD analysis primarily in order to support intake port design.
Shell Global Solutions (UK)	Provided knowledge of auto-ignition phenomenon, base fuel for engine development including full fuel analysis, detailed lubricant analysis to aid in interpretation of engine wear, and designed and interpreted a test matrix of fuel formulations in a thorough program to screen engine response to various fuel properties.
University of Bath	Conducted all of the testing, having dedicated boosting and cooled exhaust gas recirculation (EGR) rigs which were used for the initial testing of the demonstrator engine and for fuels testing work.
University of Leeds	Developed their auto-ignition model to assist with the 1-D modeling process.
Imperial College London	Specified the charging system components, with support from both JLR and Lotus, and tested them in order to characterize them accurately so that the 1-D model was as robust as possible.



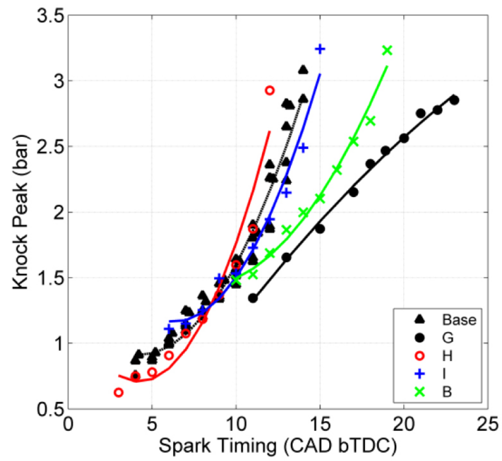
(a) Region 1A: 0% EGR, 2000 rpm, High load.



(c) Region 3A: Low back pressure (1.7 bar), 3000 rpm, High load.

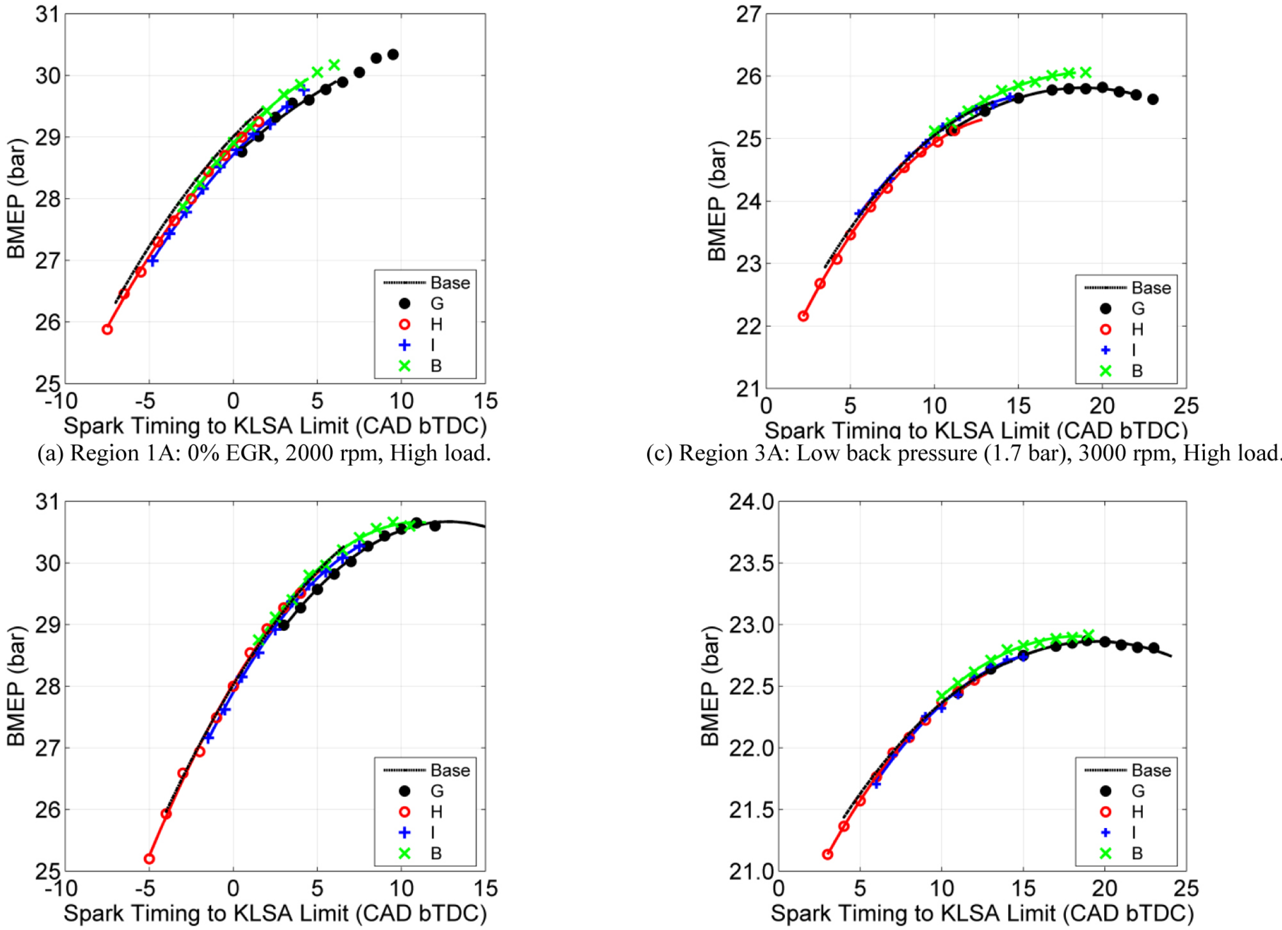


(b) Region 1B: 10% EGR, 2000 rpm, High load.



(d) Region 3B: High back pressure (2.2 bar), 3000 rpm, High load.

Figure A.1. Knock Limited Spark Advance for Fuels Base (Black, solid triangles), G (black, solid circles), H (red, open circles) and I (blue, +), and B (green, crosses) for (a) Region 1A, (b) Region 1B, (c) Region 3A and (d) Region 3B. Lines represent quadratic fits to data. KLSA was determined when KP=2 at 2000 rpm or KP=3 at 3000 rpm.



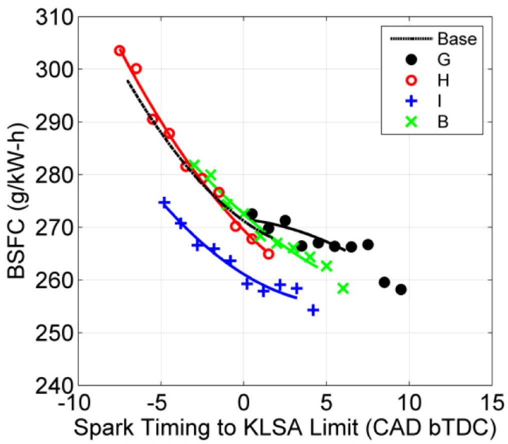
(a) Region 1A: 0% EGR, 2000 rpm, High load.

(c) Region 3A: Low back pressure (1.7 bar), 3000 rpm, High load.

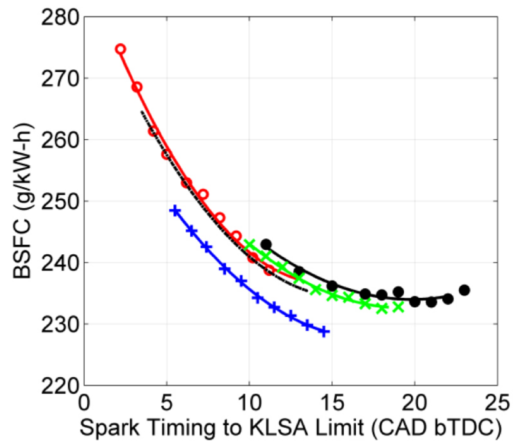
(b) Region 1B: 10% EGR, 2000 rpm, High load.

(d) Region 3B: High back pressure (2.2 bar), 3000 rpm, High load.

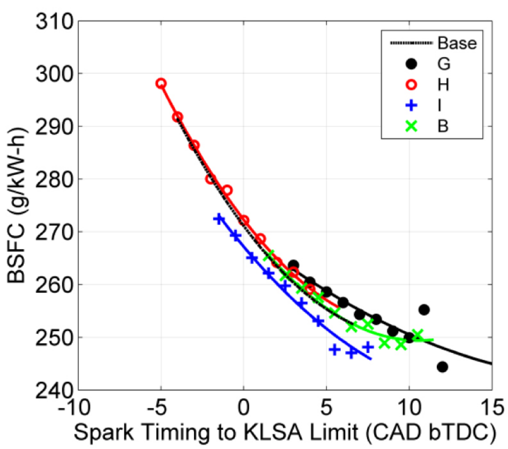
Figure A.2. Brake Mean Effective Pressure Fuels Base (Black, dashed), G (black, solid circles), H (red, open circles), I (blue, +), and B (green, crosses) for (a) Region 1A, (b) Region 1B, (c) Region 3A and (d) Region 3B. Lines represent quadratic fits to data, extrapolated or interpolated to KLSA spark timing.



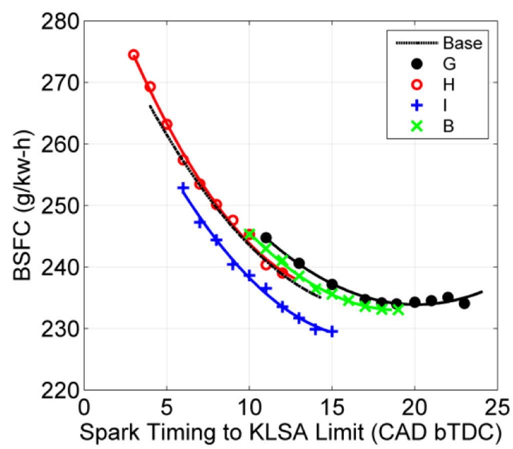
(a) Region 1A: 0% EGR, 2000 rpm, High load.



(c) Region 3A: Low back pressure (1.7 bar), 3000 rpm, High load.



(b) Region 1B: 10% EGR, 2000 rpm, High load.



(d) Region 3B: High back pressure (2.2 bar), 3000 rpm, High load.

Figure A.3. Brake Specific Fuel Consumption for Fuels Base (Black, dashed), G (black, solid circles), H (red, open circles), I (blue, +), and B (green, crosses) for (a) Region 1A, (b) Region 1B, (c) Region 3A and (d) Region 3B. Lines represent quadratic fits to data, extrapolated or interpolated to KLSA spark timing.